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Fatigue Crack Initiation from Pitting Introduced during the Anodising Process

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ABSTRACT

This report discusses four examples of Australian Defence Force aircraft components manufactured from aluminium alloys that exhibited surface pitting arising from the anodising process. In three of the examples, the anodising pits acted as initiation sites for fatigue cracks, which ultimately led to failure of the components. The information presented in this report highlights the issue of anodising pitting and the associated potential for fatigue cracking which can extend to entire batches of anodised components.

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Fatigue Crack Initiation from Pitting Introduced during the Anodising Process

Executive Summary

Fatigue cracking is by far the most common cause of failure for aircraft components. The presence of a surface defect that acts as a crack initiation site considerably reduces the fatigue life of the component. Surface defects that arise as a result of pitting during the anodising process are of concern because pitting will be present on the entire surface of the component, increasing the likelihood that fatigue crack growth will occur.

Anodised aluminium alloy components are used extensively throughout the Australian Defence Force's (ADF) aircraft fleet and in most cases the anodising process will have been performed correctly. Anodising remains an effective corrosion protection method for aluminium alloy components, however it needs to be recognised, particularly by original equipment manufacturers (OEMs), that process control is crucial so that the benefits of anodising are not lost due to the formation of excessive etch pits. This is especially so given that anodising is a batch treatment and therefore problems with a single batch can extend to numerous parts. This could potentially lead to a shortage of spares should an entire batch need to be rejected, or more importantly, could result in an entire batch of components developing cracking while in service.

This report presents examples of components from ADF aircraft that exhibited surface pitting which formed during the anodising pre-treatment process. In three of the examples, fatigue cracking had initiated from the surface pits leading to failure of the components.

Awareness of the problems that can be associated with anodising may assist in identifying defective components and thereby minimise the impact of anodising pitting defects on the ADF fleet.

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Cathy Smith graduated from Monash University, Melbourne in 2004 having obtained a Bachelor of Engineering (Materials) with honours. Following 5 years at Rio Tinto as a Research Engineer specialising in aluminium products, Cathy joined DSTO in 2010 within the area of Aircraft Forensic Engineering and Accident Investigation. Since then Cathy has been involved in numerous investigations of ADF aircraft component and systems failures, including engine failures and accident investigation.

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1. Introduction

Fatigue cracking is by far the most common cause of failure for aircraft components, accounting for approximately 60% of failures [1]. Fatigue life is made up of two stages, being crack initiation, which was traditionally considered to account for a majority of the fatigue life, and crack propagation. The presence of a surface defect that acts as a crack initiation site eliminates the initiation phase of fatigue life, and thereby considerably reduces the fatigue life of the component. All manufactured aircraft components will contain surface defects of some type, and therefore in practice the initiation phase of fatigue life can be omitted.

Surface defects can arise during manufacture (such as machining marks, burrs, forging laps and folds, casting porosity or folds, etch pitting, etc.) and in-service (including scratches, dents, impacts, corrosion, chipping, erosion, etc.). If the location of a surface defect coincides with an area of sufficiently high alternating stress, fatigue crack growth from the defect can occur. In the case of etch pitting that is introduced during the anodising process, pits are present over the entire surface of the component. This means that there is an increased likelihood that pits will exist in high stress areas, and that multiple cracks will initiate from the pits. These cracks can quickly join to form a larger crack, further reducing the fatigue life.

This report presents examples of components from Australian Defence Force (ADF) aircraft that exhibited surface pitting formed during the anodising pre-treatment process. In three of the examples, fatigue cracking had initiated from the surface pits leading to failure of the components.

2. Anodising

Anodising is an electrolytic process that causes controlled growth of amorphous aluminium oxide (Al_2O_3) on the surface of aluminium alloys [2]. This oxide layer provides a barrier to protect the component from corrosion. In particular, an anodised aluminium alloy component is highly resistant to atmospheric and salt-water attack. Apart from improved corrosion resistance, anodising can also be used to increase abrasion resistance, increase paint adhesion, improve adhesive bonding and provide electrical insulation [3].

The most common processes used to generate an anodised coating are Chromic Acid (Type I) and Sulphuric Acid (Type II) anodising. Sulphuric acid is the most widely used anodising process for aluminium alloys due to its low operating costs and ability to produce coating thicknesses up to 25 μm . Chromic acid anodic coatings are usually limited to thicknesses of 0.5 – 3 μm . However, due to the corrosive nature of sulphuric acid, chromic acid anodising is the preferred process for components such as riveted or welded assemblies where it is difficult to remove all of the anodising solution. In addition, chromic acid anodising is used for components with tight dimensional tolerances where a thick anodised layer is undesirable. Chromic acid anodising yields a yellow to dark olive finish depending on thickness whereas sulphuric acid anodising produces a clear coating [4].

Anodising treatments typically require eight to ten process stages, incorporating pre- and post-anodising processing. The first stages of the process usually include degreasing and alkaline cleaning, high-pH caustic etching and low-pH acidic desmutting. These steps are all designed to produce a chemically clean surface, free of all grease and oil, corrosion

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products and the naturally occurring aluminium oxide. The cleaning methods selected are based on the type of soils or contaminants that must be removed [3]. Following cleaning, the component is anodised and sealed [5]. Table 1 summarises a typical anodising sequence.

Table 1: Typical anodising sequence [3, 5]

Operation	Solution	Purpose	Temperature (°C)	Time (min)
Degrease & clean	Solvent, alkaline cleaner	Removes oils and grease as well as solid dirt particles	As required	As required
Rinse	Water		Ambient	1
Chemical etch	Caustic solution	Removes the natural oxide layer from the aluminium. This allows for a more conductive surface for subsequent anodising. A residue is normally deposited on the surface from the elements that are not soluble in the solution (e.g. Fe, Cu, Si, Zn, Mg)	38 - 71	0.5 - 2
Rinse	Water		Ambient	1
Desmut	HNO ₃ + Fe ₂ (SO ₄) ₃	Removes the residue produced in the chemical etch step	Ambient	2-10
Rinse	Water		Ambient	1
Anodise	Chromic acid: 3 - 10 wt% CrO ₃ in water; or Sulphuric acid: 12 - 20 wt% H ₂ SO ₄ in water	Produces a porous aluminium oxide surface layer	32-35	30
Rinse	Water		Ambient	1
Seal	Deionised Water	Closes the pores in the aluminium oxide surface layer	90-100	10-15
Dry	Hot Air		105 maximum	As required

While anodising surface treatments are applied to extend service life via corrosion protection, they can sometimes have the opposite effect. For instance, the anodised layer has been recognised as reducing fatigue life due to its brittle and porous nature and because of the tensile residual surface stresses induced during anodising. The brittle coating readily cracks when loaded, and micro-cracks in the coating may result in early fatigue crack initiation [6]. In addition, it has been found that exposure to the pre-treatment cleaning solutions used in the anodising process can result in pitting attack of aluminium alloys [5]. If the composition or temperature of the treatment baths is not correct, or if the components remain in a bath for too long, excessive pitting may result. As anodising is performed in batches, all components produced in the same batch would suffer similar surface pitting attack.

Pitting attack during anodising pre-treatments usually occurs where constituent particles or grain boundaries intersect the surface of the component. This is due to differences in the chemical potentials of the particles and grain boundaries compared to the surrounding aluminium matrix. Pits can readily form by the selective dissolution of the matrix around the constituent particles / grain boundary or by dissolution of the particles / grain boundaries themselves [7]. This type of pit is referred to as an etch pit. The pits can subsequently act as stress concentrators and crack initiation sites during service loading.

3. Service Examples

3.1 Rotary Aircraft Wheel

The left hand forward inboard wheel from an ADF rotary wing aircraft was found to be fractured during scheduled Daily Flight Servicing [8]. Figure 1 shows the wheel following removal of the tyre. A section comprising approximately one third of the circumference of the rim had broken away from the wheel at the bead seat and was located on the taxiway. The wheel had been in service for 1798 airframe hours (AFHRS) and was manufactured from aluminium alloy 2014-T6 with a sulphuric acid anodising surface treatment.



Figure 1. Photograph of the wheel following removal of the tyre. A section comprising approximately one third of the circumference had separated from the wheel at the bead seat.

Examination of the fracture surface revealed the presence of progression marks and tear bands, indicative of fatigue cracking, see Figure 2. The area of fatigue cracking extended approximately 85 mm around the circumference of the wheel before final tensile failure occurred. It was observed that numerous fatigue cracks had initiated on the outer surface of the wheel and propagated inwards. Higher magnification examination revealed surface etch pits up to 40 µm diameter and 40 µm depth, and corrosion pits up to 300 µm in diameter and 100 µm in depth, at the origins of the fatigue cracks. Paint was observed within these pits, see Figure 3.

Following removal of the paint from a section of the wheel, it was observed that the surface of the wheel was extensively pitted, with smaller rounded etch pits and larger corrosion pits present, see Figure 4 and Figure 5. The size of these pits was consistent with the pits observed at the fatigue crack origins.

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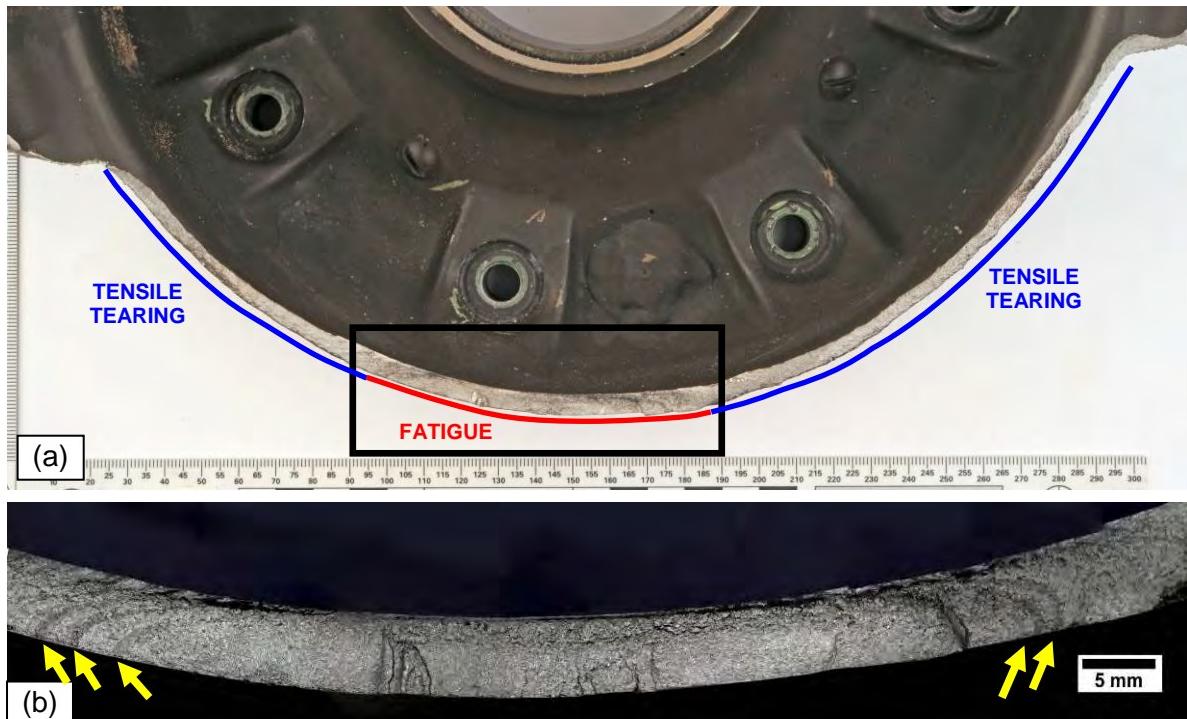


Figure 2. Photographs of (a) the fracture surface of the wheel with the areas of tensile tearing indicated with blue lines and the area of fatigue indicated with a red line, and (b) a higher magnification image of the fatigue region (area boxed black in (a)). Tear bands at the outer edges of the fatigue region are indicated with yellow arrows.

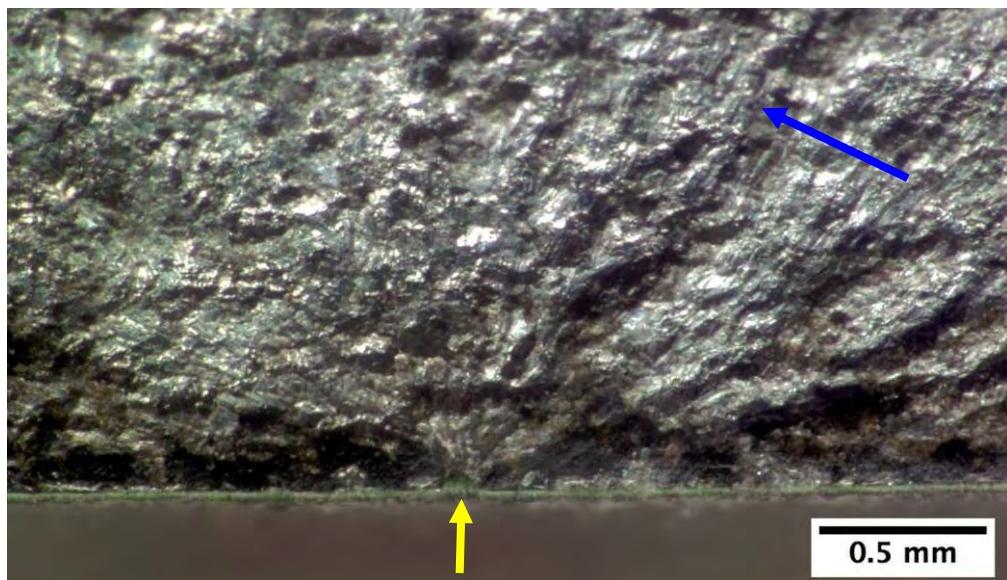


Figure 3. Photograph of a fatigue crack observed on the fracture surface. A fatigue progression mark is indicated with a blue arrow. The pit at the origin of the crack (approximately 40 μm in depth), which was observed to have been painted, is indicated with a yellow arrow.

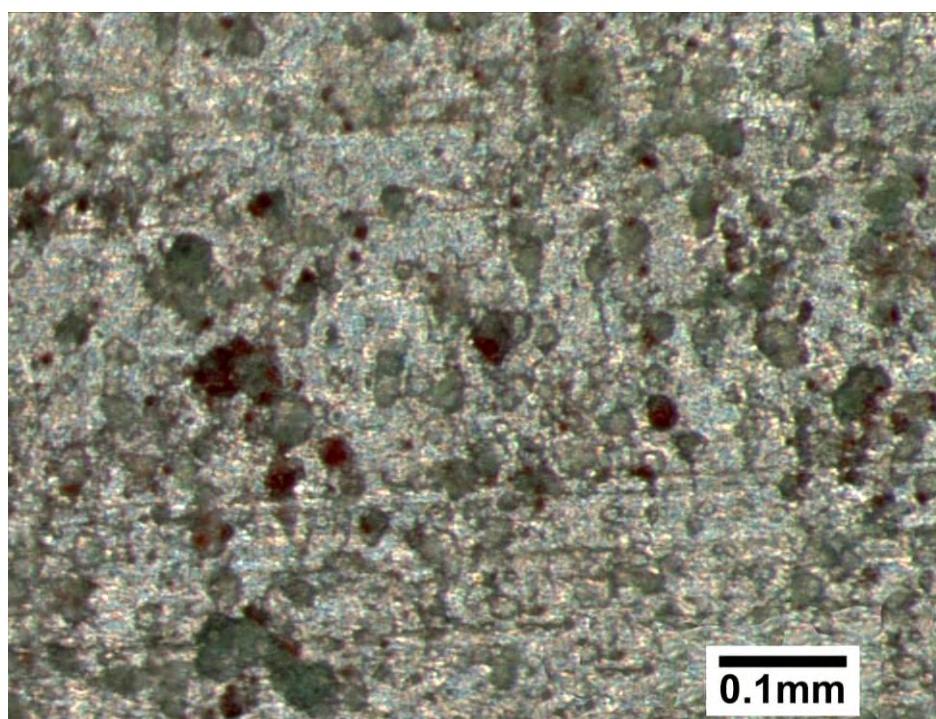


Figure 4. Photograph of the outer surface of the wheel following paint removal. The surface exhibited extensive rounded etch pits up to $40 \mu\text{m}$ diameter.

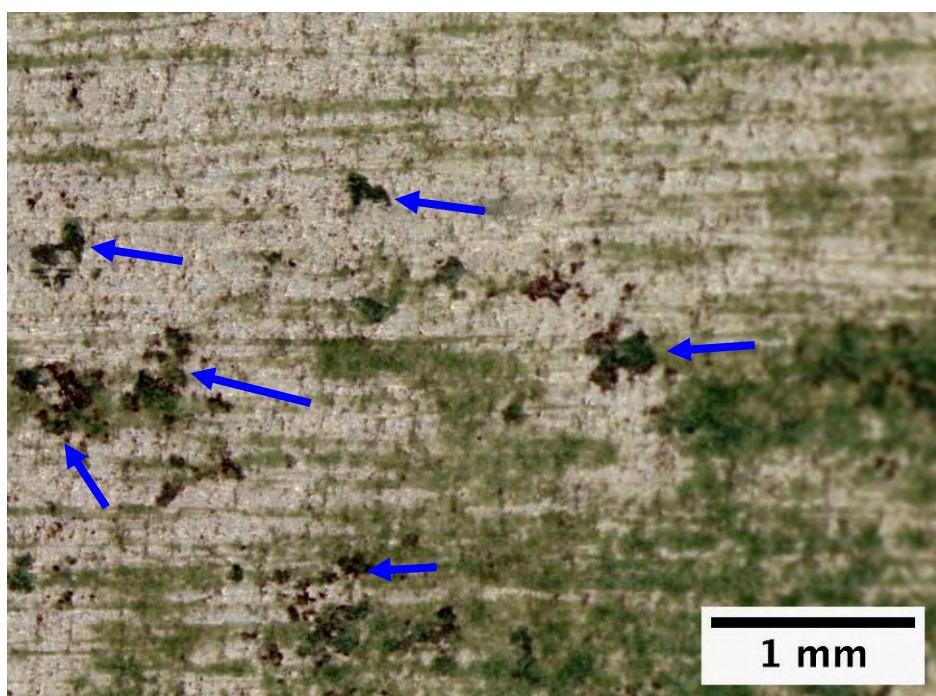


Figure 5. Photograph of the outer surface of the wheel following paint removal showing dispersed corrosion pits, indicated with blue arrows.

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Scanning Electron Microscope (SEM) examination of the fracture surface confirmed that the failure mode was consistent with fatigue, with progression marks present over the fracture surface, see Figure 6. Examination of the corrosion and etch pits present at the crack initiation sites revealed that they had been anodised and painted, see Figure 7 and Figure 8, which indicated they were present at production.

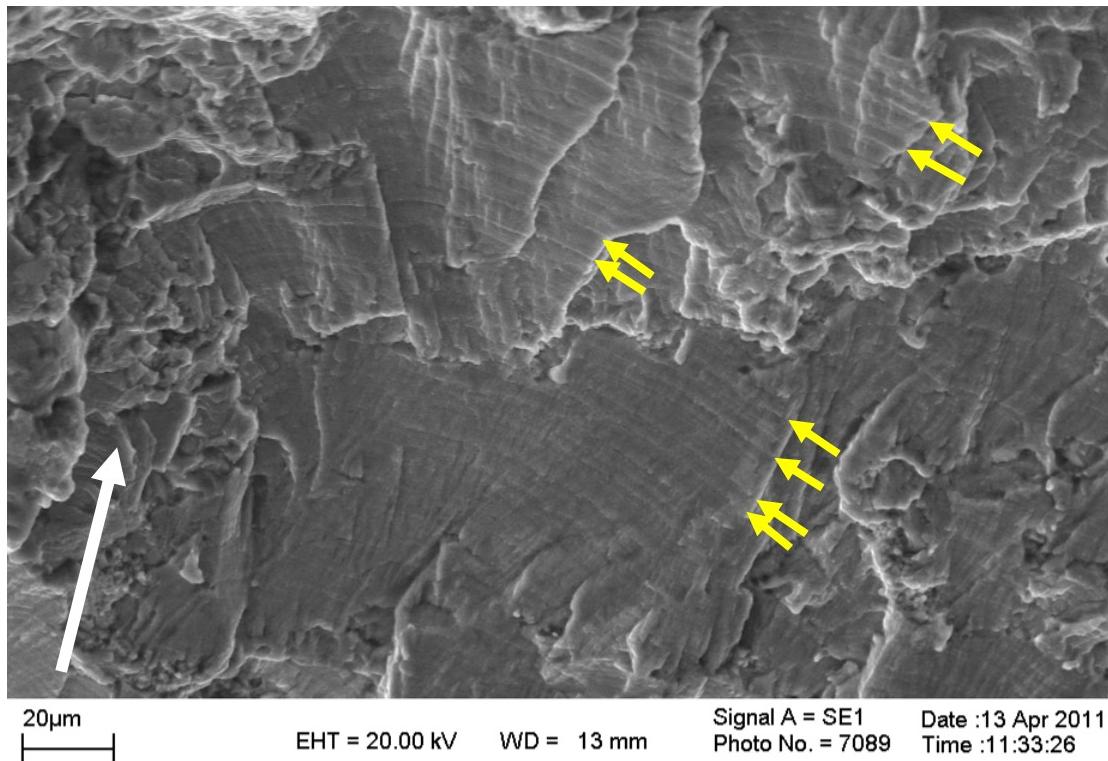


Figure 6. SEM photograph of the fracture surface on which numerous progression marks were observed, examples indicated with yellow arrows. Crack growth direction is indicated with a white arrow.

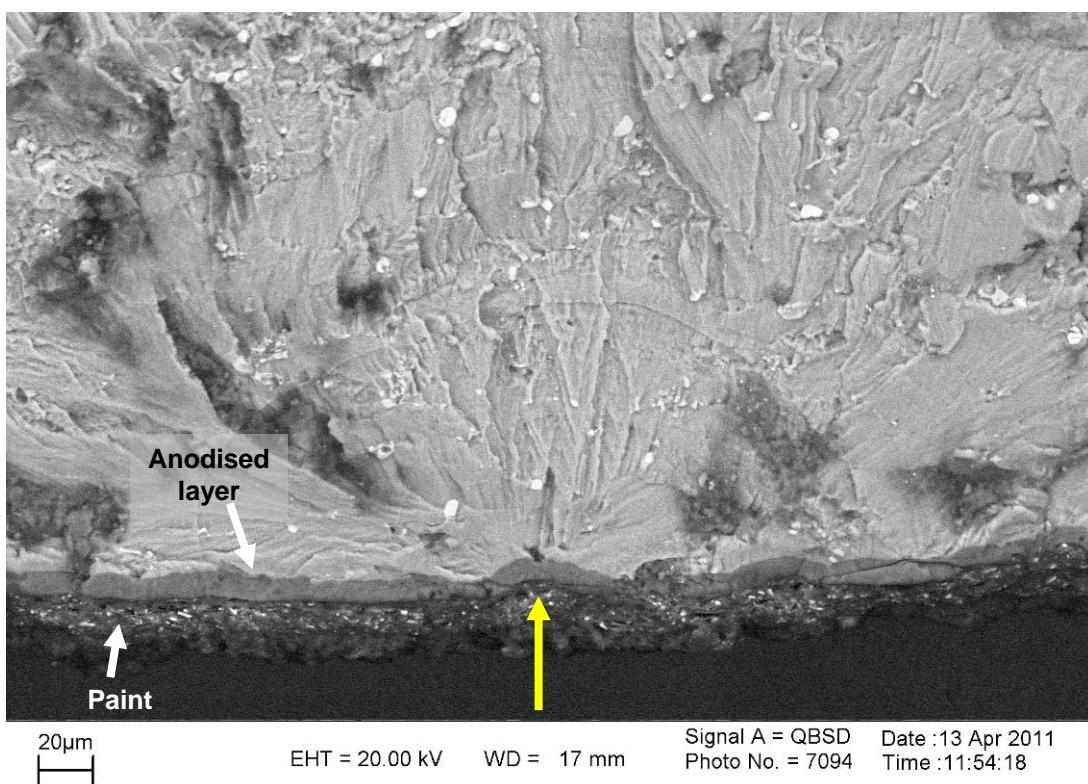


Figure 7. SEM photograph showing a fatigue crack that initiated from a surface pit (8 µm depth), indicated with a yellow arrow. The pit was observed to be both anodised and painted.

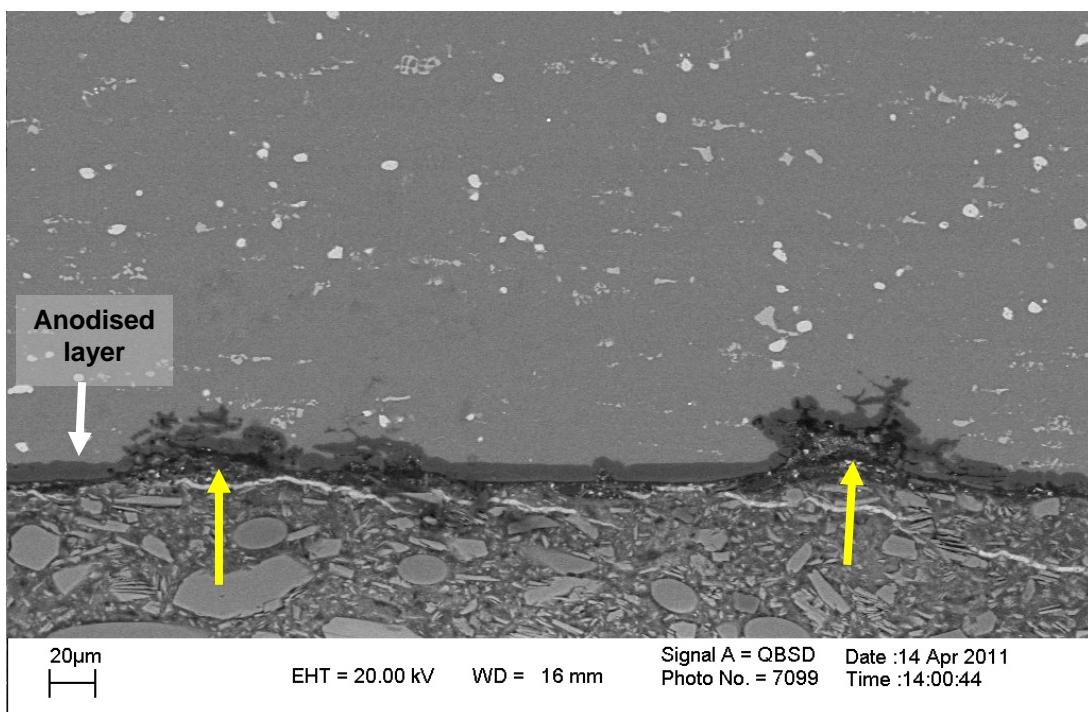


Figure 8. SEM photograph showing two corrosion pits in cross-section, indicated with yellow arrows. The surfaces of the pits were found to have been anodised.

Failure of the wheel occurred at the bead seat radius, which is typically a region of high bending stress and is therefore prone to initiation and growth of fatigue cracks, with small surface defects providing the crack initiation sites. Operational stresses arising during aircraft landing and taxiing provided the driving force for crack propagation.

Fatigue cracking had initiated from etch and corrosion pits present on the wheel's external surface. The etch and corrosion pits were anodised and painted, indicating that they had formed prior to anodising. The existence of etch pits over all surfaces suggests that they likely formed when the wheel was immersed in a bath during a pre-anodising process. The corrosion pits likely grew from etch pits due to environmental exposure prior to surface finishing.

As the wheel was supplied by the manufacturer in the anodised condition, and the etch pits present on the surface formed during the pre-anodising treatments, it is likely that other wheels anodised in the same batch would also exhibit surface pitting.

3.2 Oil Filler Adapter

During removal of the gearbox oil filler assembly from an ADF rotary wing aircraft, the first thread of the oil filler adapter was found to have fractured [9]. Two failures of this type had previously occurred. The adapter, shown in Figure 9, was manufactured from aluminium alloy L168-T6 (equivalent to AA 2014) with a chromic acid anodising surface treatment.

Following cleaning, the fracture surfaces on the first thread were examined and found to be consistent with fatigue cracking, see Figure 10. The cracks had initiated at corrosion pits up to 80 µm diameter and 30 µm depth at the thread roots, see Figure 11. SEM examination of the fracture surfaces confirmed cracking was via fatigue, with numerous progression marks present, see Figure 12 for example, and corrosion pits present at the crack initiation sites, see Figure 13.

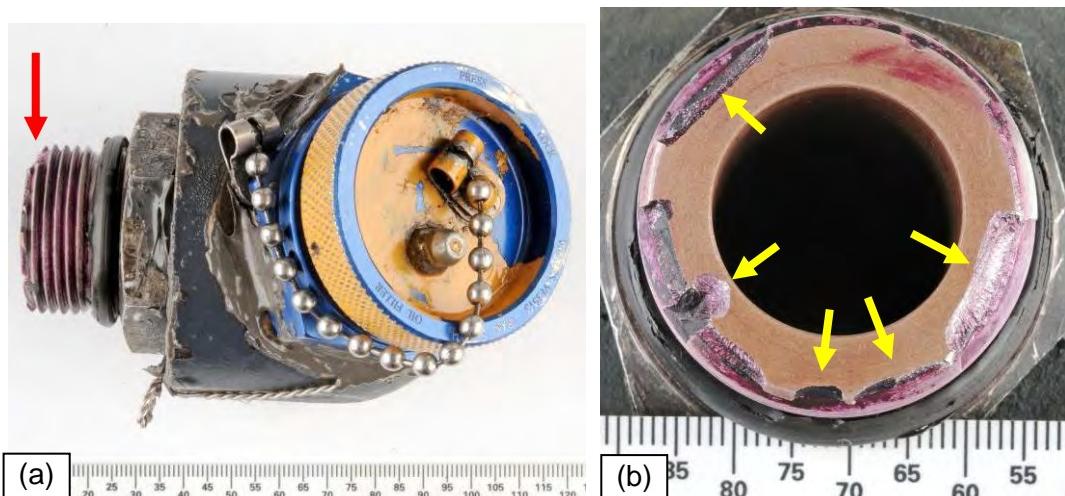


Figure 9. Photographs of the oil filler adapter as received. The first thread was fractured, as indicated with a red arrow in (a). Fracture occurred in several locations, examples indicated with yellow arrows in (b).

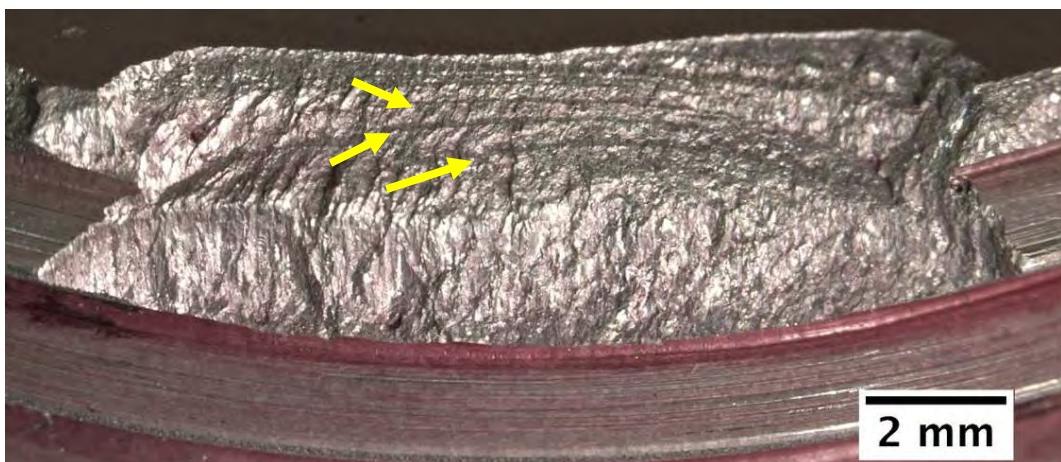


Figure 10. Photograph of the cracking present on the first thread. The cracking originated at the thread root and was consistent with fatigue. Examples of progression marks are indicated with yellow arrows.

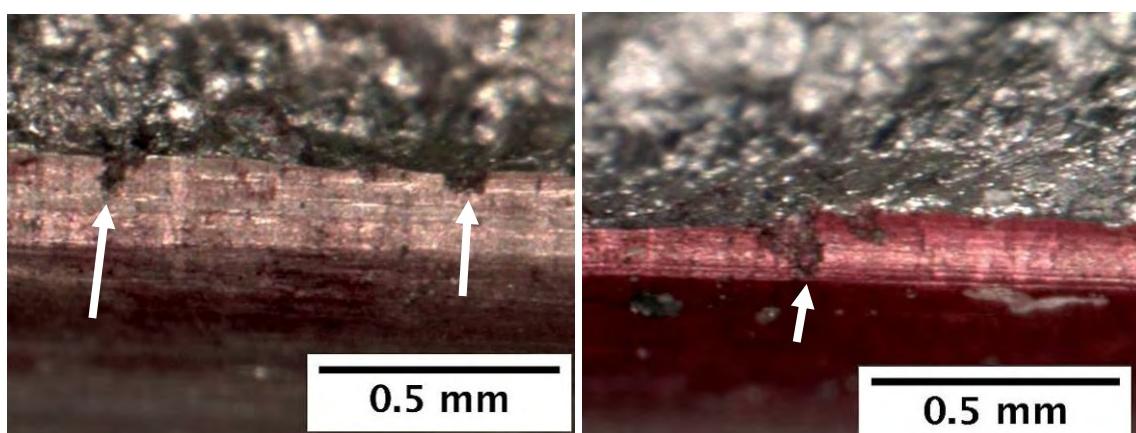


Figure 11. Photographs of pitting (arrowed white) observed at the initiation sites of the fatigue cracks. Corrosion pits up to 80 μm diameter and 30 μm depth were observed.

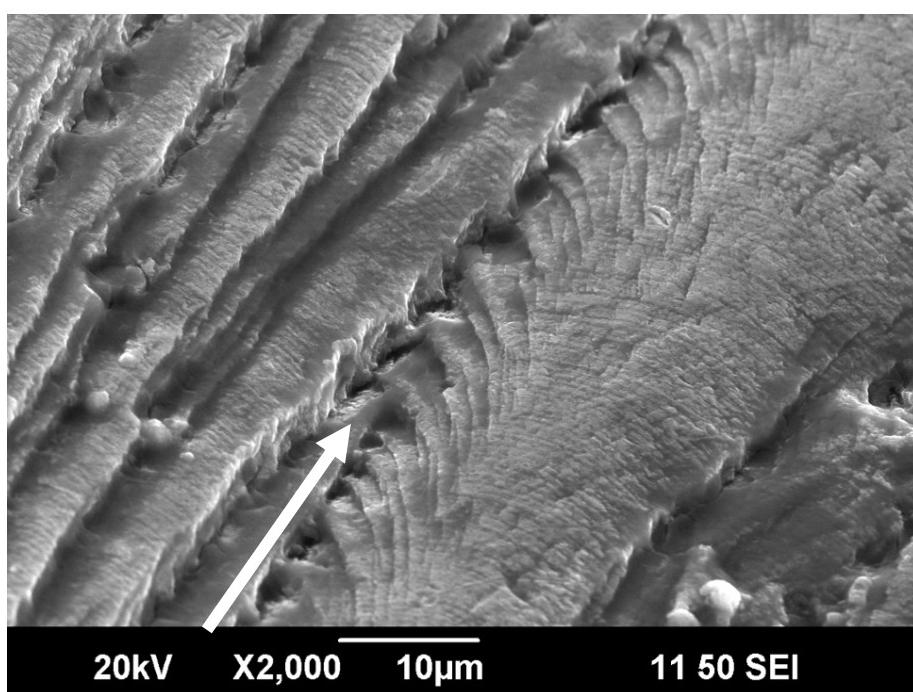


Figure 12. SEM photograph of the fracture surface showing the numerous progression marks, appearing as a series of curved bands on the surface. Crack growth direction is indicated with a white arrow.

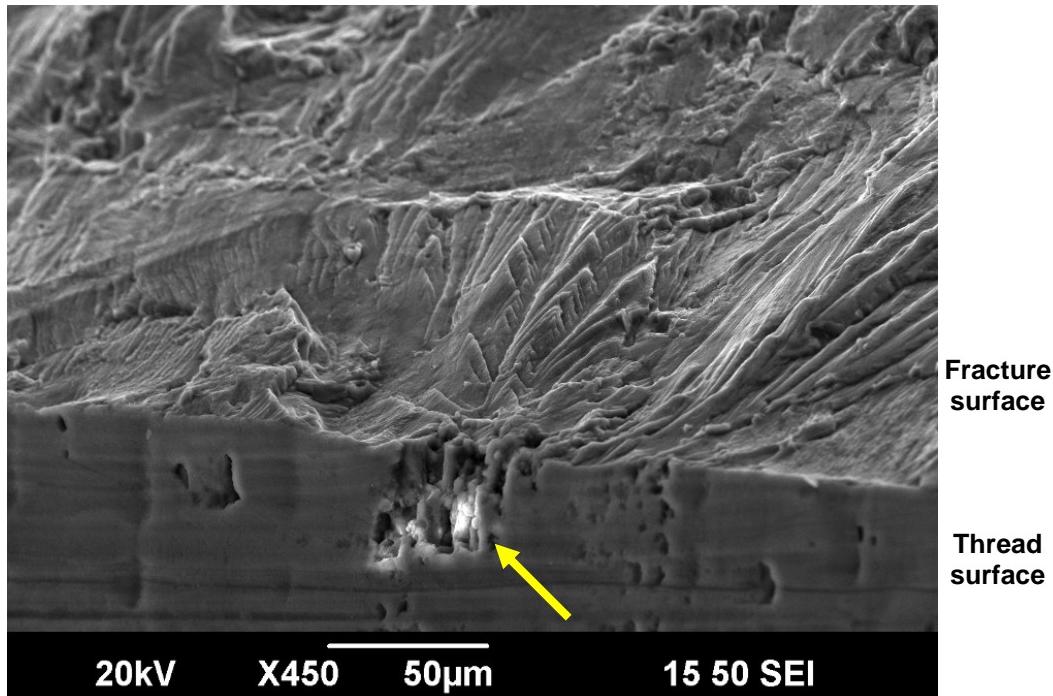


Figure 13. SEM photograph showing fatigue crack initiation from a surface pit (arrowed yellow).

Cross-sections cut through the threaded section of the oil filler adapter revealed the presence of fine etch and larger corrosion pits on the threads, see Figure 14 and Figure 15. The surfaces of the etch pits were anodised while the corrosion pits were only partially anodised, which indicated that further corrosion and growth of the pits had occurred following anodising.

The etch pits would provide ideal sites for the initiation of corrosion pits due to environmental contamination prior to anodising. In addition, the presence of the etch pits may have caused discontinuities in the anodised surface layer, making the component susceptible to localised corrosion and corrosion pitting following anodising.

The pits acted as stress concentrators for crack initiation, with stresses arising from normal operations providing the driving force for crack growth. As the component was supplied by the manufacturer in the anodised condition, other oil filler adapters from the same batch were likely to suffer from significant etch and corrosion pitting.

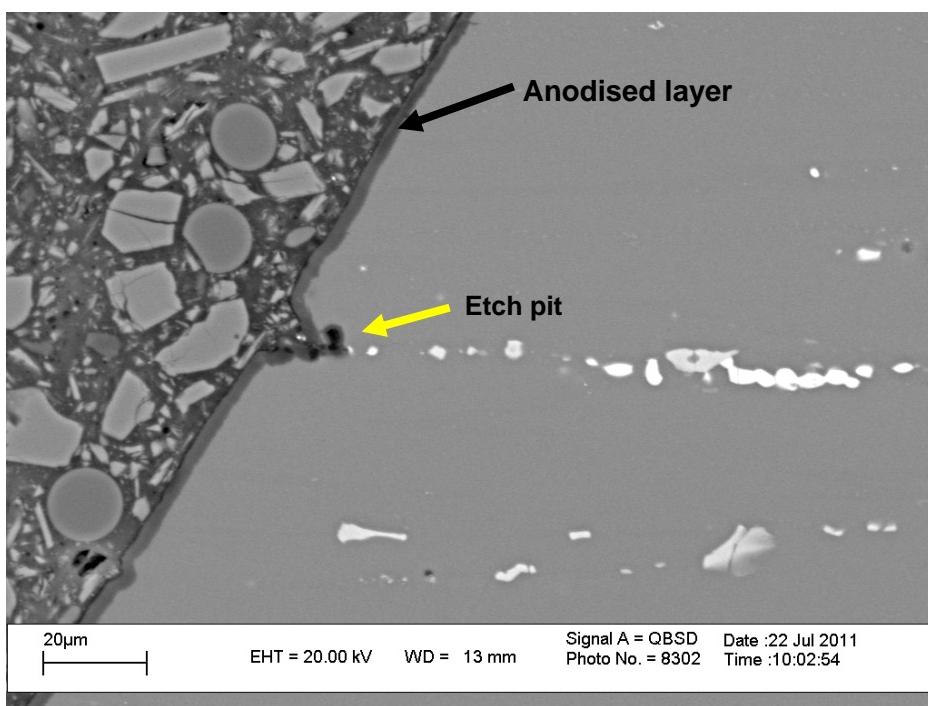


Figure 14. SEM photograph of etch pitting observed in a polished metallographic cross-section through the oil filler adapter. The surfaces of the pits were anodised. Pits were observed to be up to 12 µm in diameter and 10 µm in depth.

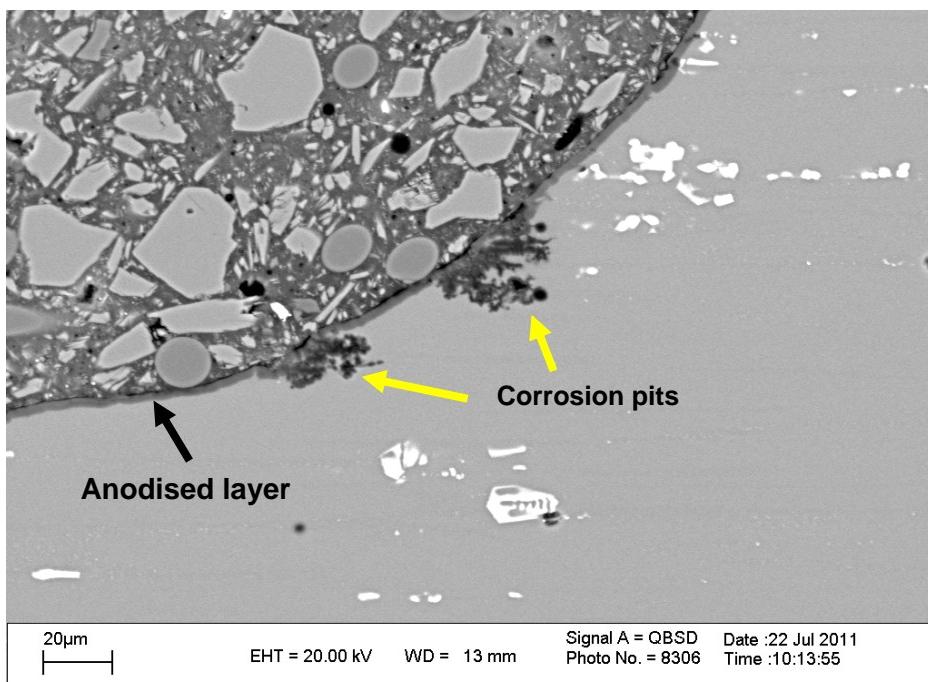


Figure 15. SEM photograph of corrosion pitting observed in a polished metallographic cross-section through the oil filler adapter. An anodised layer was present at the surface and within the pits.

3.3 Main Landing Gear Retractor Actuator

Cracking was observed on the hydraulic cylinder of the left hand retractor actuator from the main landing gear of an ADF fixed wing aircraft [10]. The crack ran along the length of the cylinder and was found to be 163 mm long, see Figure 16. The hydraulic cylinder was manufactured from aluminium alloy 2014 in the T6 condition.

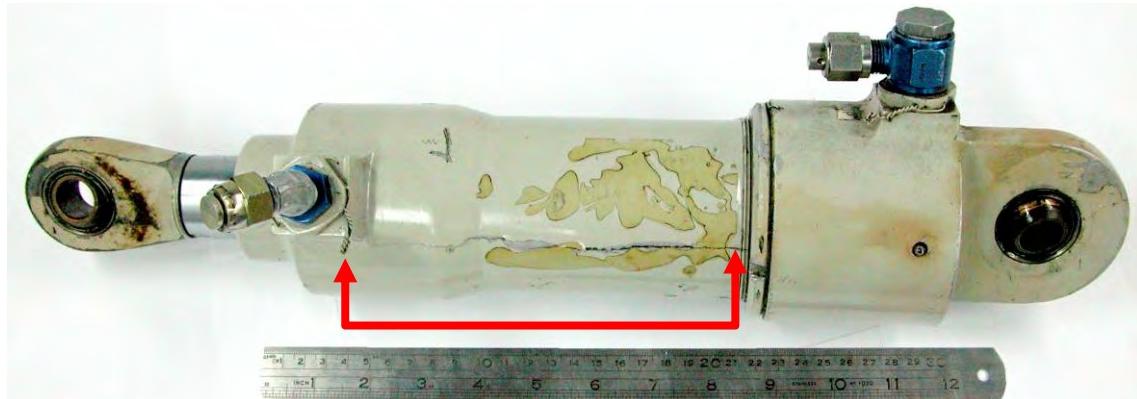


Figure 16. Photograph of the main landing gear hydraulic cylinder. A 163 mm crack was present along the length of the cylinder, as indicated with a red arrow.

Examination of the fracture surfaces revealed the presence of multiple cracks in the wall of the cylinder, see Figure 17. Progression marks were present on the fracture surfaces indicating that the cracking had propagated via fatigue. Based on the orientation of the progression marks, the crack originated from the bore of the cylinder and propagated towards the outer surface.

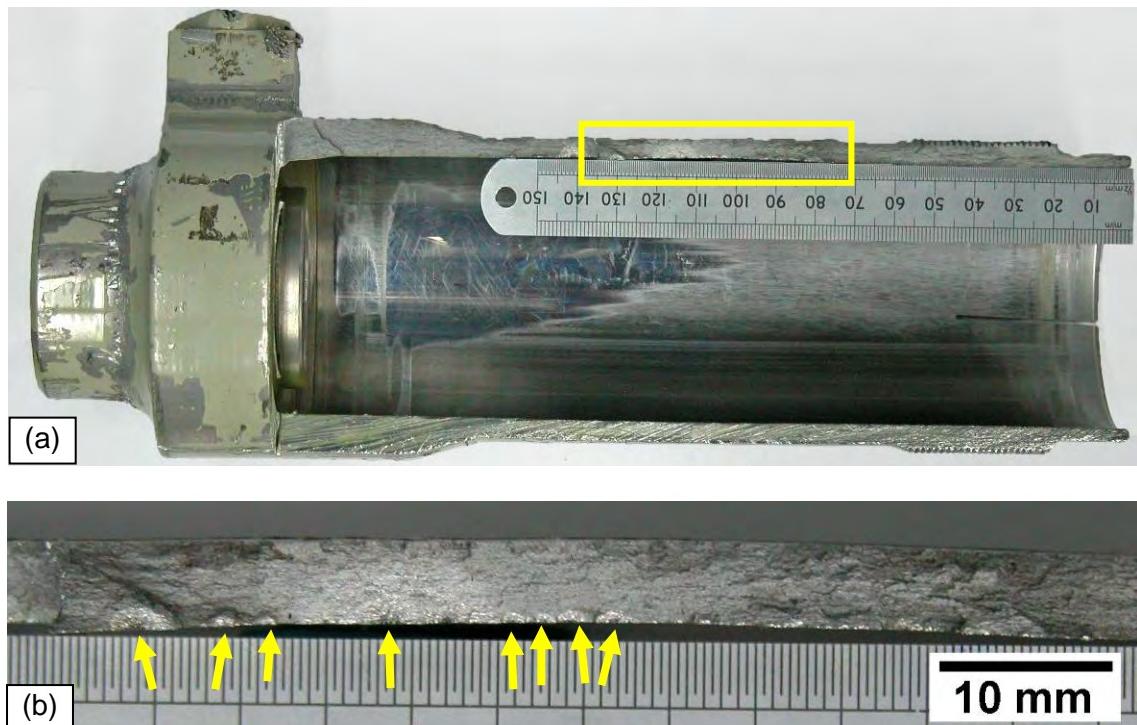


Figure 17. Photographs showing the fracture surface of the hydraulic cylinder. The area marked with a yellow box in (a) is shown at higher magnification in (b). Multiple crack initiation sites were observed, with examples indicated with yellow arrows.

SEM examination of the fracture surface revealed that multiple cracks had propagated from pits in the surface of the bore of the cylinder, see Figure 18. The pits were measured to be between 20 and 80 μm in depth. Pitting was observed over the entire surface of the cylinder bore.

Metallographic examination of cross-sections from selected areas of the cylinder confirmed the presence of pitting damage to the bore of the cylinder. The surface of the pits exhibited evidence of anodising, see Figure 19. This indicated that the pits were present in the cylinder when the cylinder was last anodised, being either at manufacture or overhaul. The pits provided crack initiation sites and the cracks grew undetected from the inside of the bore.

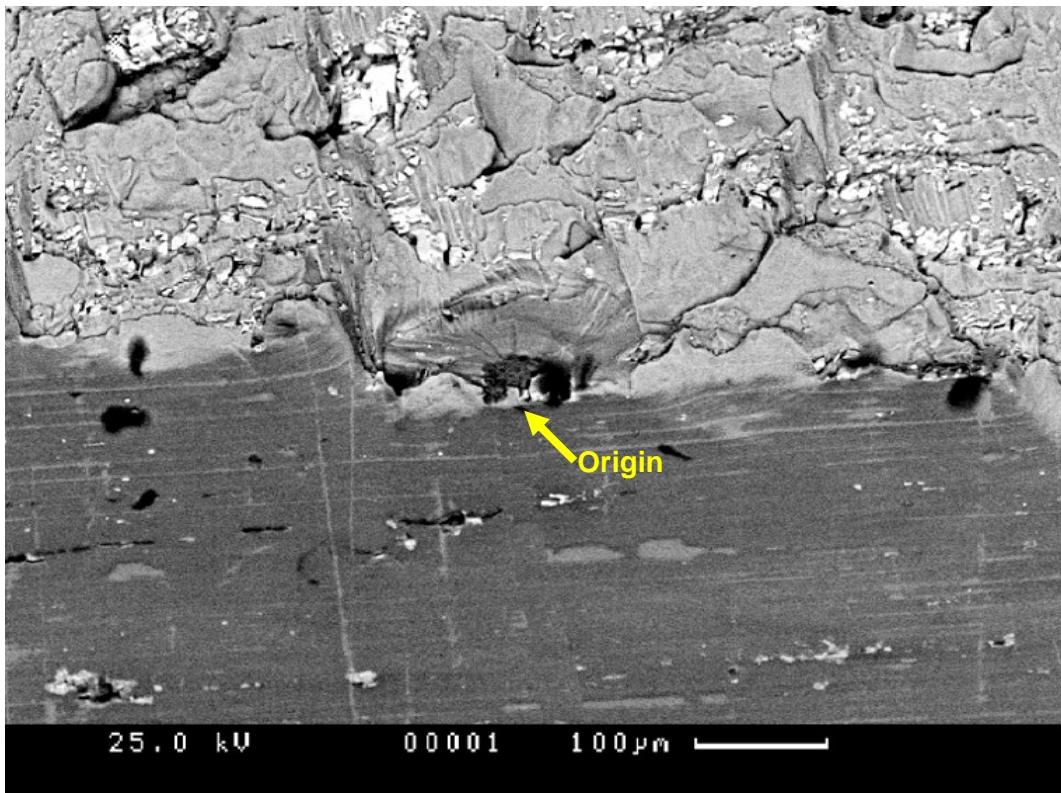


Figure 18. SEM photograph showing one of the crack origins. Cracking had initiated at a pit, which appears as a dark area at the origin.

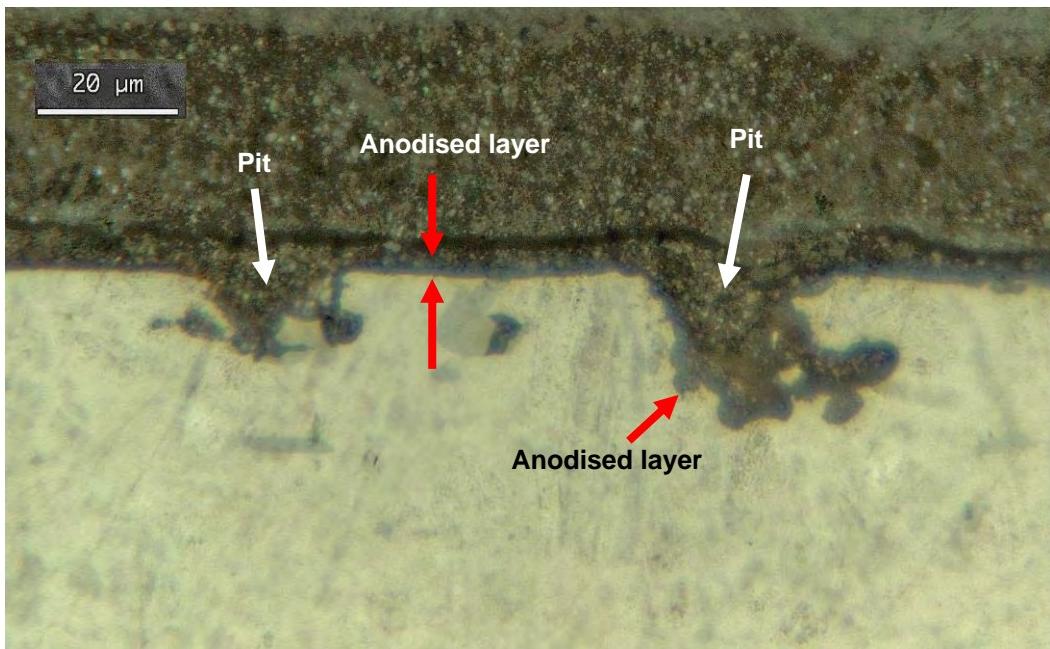


Figure 19. Photograph of pitting (depths of 11 μm and 20 μm) in the surface of the cylinder bore. Note that the anodised layer is present within the pits.

3.4 Rescue Hoist Arm

During routine inspection, pitting was observed on a new rescue hoist arm for an ADF rotary wing aircraft [11]. An in-service rescue hoist arm, from the same manufacturing batch, was also inspected and found to have similar pitting. The rescue hoist arm, shown in Figure 20, was manufactured from aluminium alloy 7075-T73 with a chromic acid anodising surface treatment.

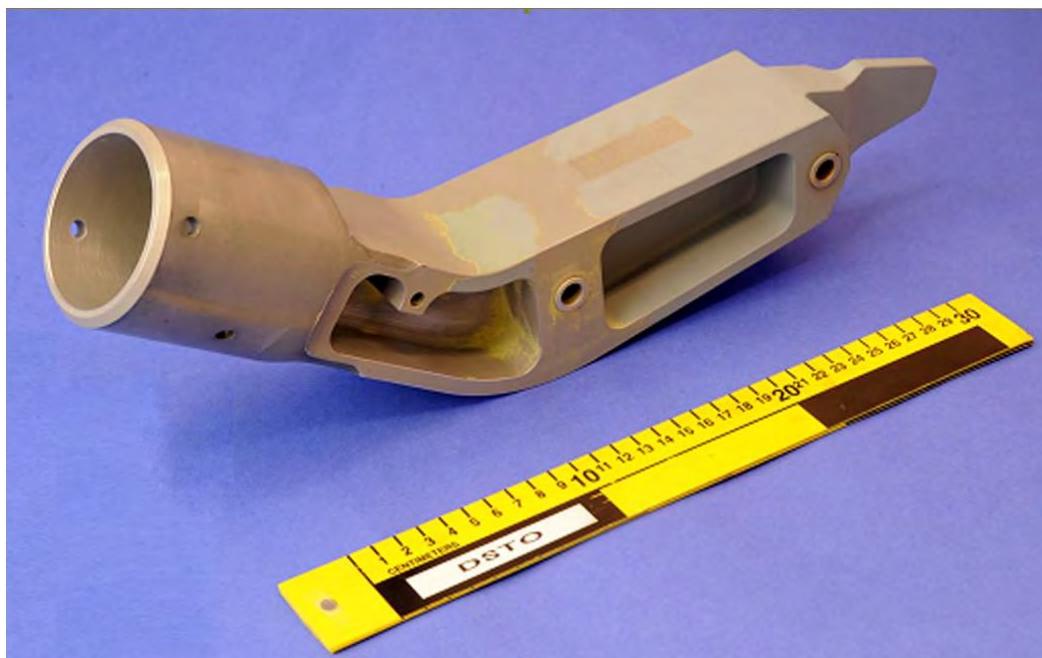


Figure 20. Photograph of the rescue hoist arm as received. The rescue hoist arm consisted of a tubular end section and a H-profile body.

Examination of the two rescue hoist arms revealed the presence of fine etch pits on all surfaces. The pits were typically 50 – 100 μm in diameter, see Figure 21. In addition to the fine etch pitting, a distribution of larger corrosion pits was observed on the outer surfaces of the rescue hoist arms, see Figure 22. The locations of the corrosion pits were generally consistent between the two rescue hoist arms, see Figure 23. The corrosion pits were up to 5 mm in length, with some containing dark coloured deposits and others being filled with paint or containing paint particles that were consistent in size and shape with the paint observed within the etch pits, see Figure 24.

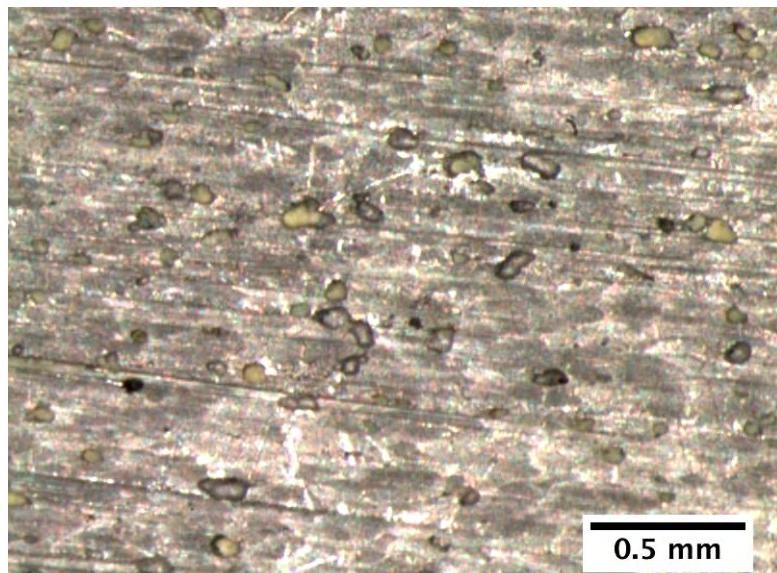


Figure 21. Photograph of fine etch pits observed on the body of the rescue hoist arms. Etch pits on the body were typically 50 – 100 μm in diameter.

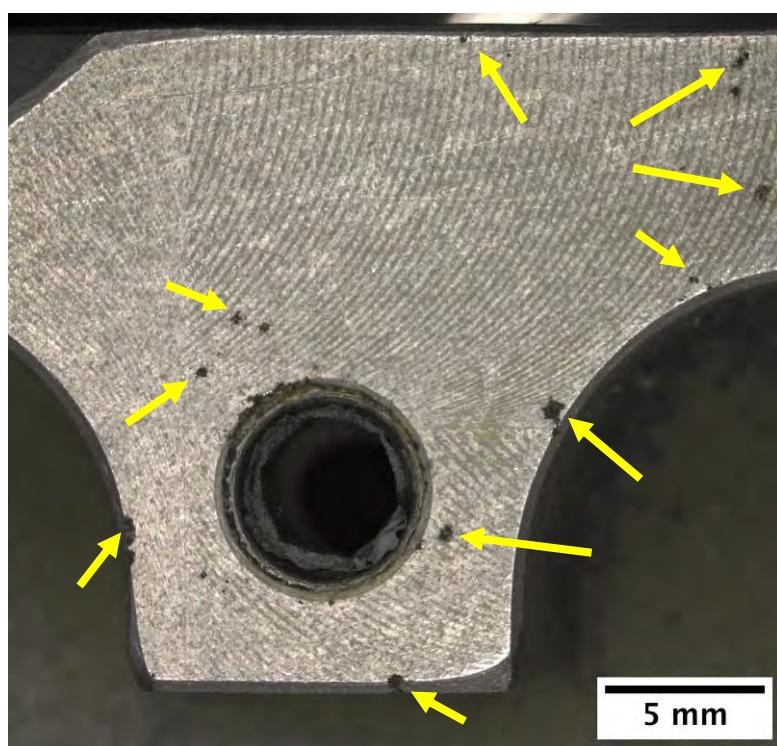


Figure 22. Photograph showing examples of the corrosion pits observed on the body of the rescue hoist arm, indicated with yellow arrows. Corrosion pits up to 5 mm in length were observed.

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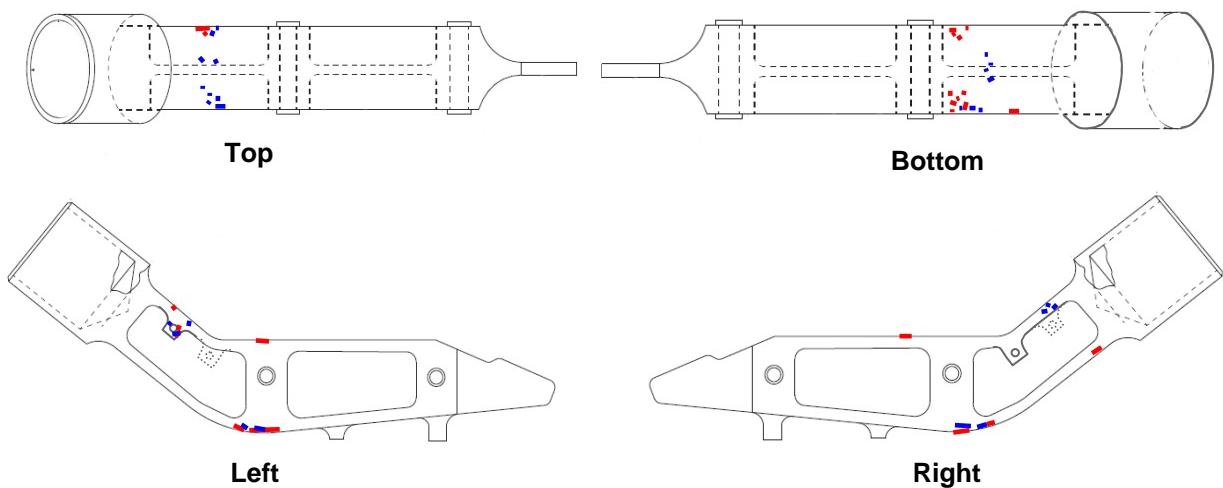


Figure 23. Diagrams showing locations of corrosion pits on each face of the rescue hoist arms. Red points indicate corrosion pits on rescue hoist arm 1 and blue points indicate corrosion pits on rescue hoist arm 2. Locations were generally consistent between the two rescue hoist arms.

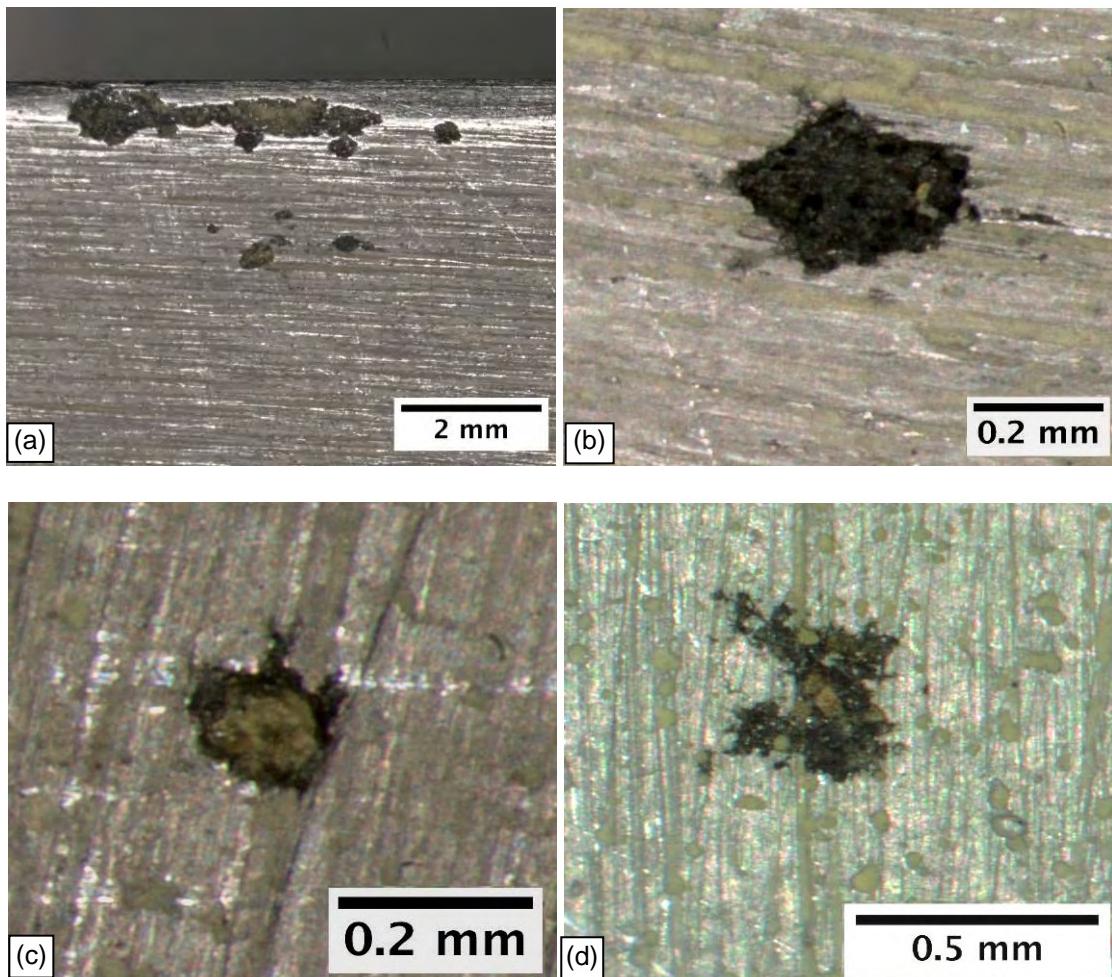


Figure 24. Photographs showing (a) corrosion pits up to 5 mm in length. The pits were observed to contain (b) dark coloured deposits, or (c) residual paint. In some cases (d) the paint within the corrosion pits consisted of particles that were similar in size and shape with the paint observed in the finer etch pits.

Cross-section examination of the etch pits revealed they had a rounded shape and a typical depth of approximately 25 μm , see Figure 25. An anodised layer was observed on the surface of the etch pits, see Figure 26. Examination of the corrosion pits in cross-section revealed that the pits were in the order of 300 μm in depth and had a branched, irregular structure, see Figure 27 for example.

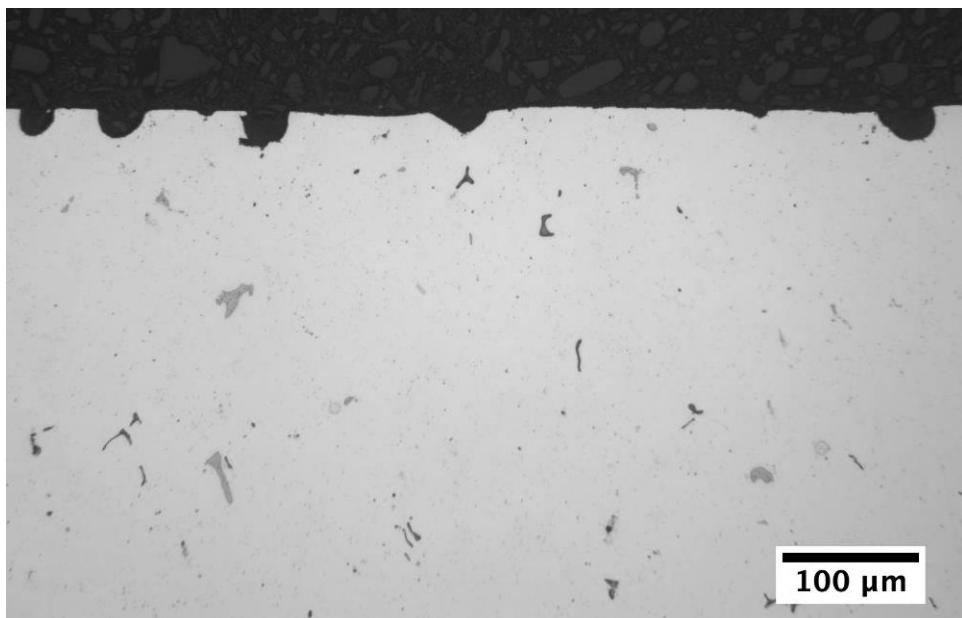


Figure 25. Micrograph of a cross-section from a rescue hoist arm showing the etch pits were up to 25 μm in depth.

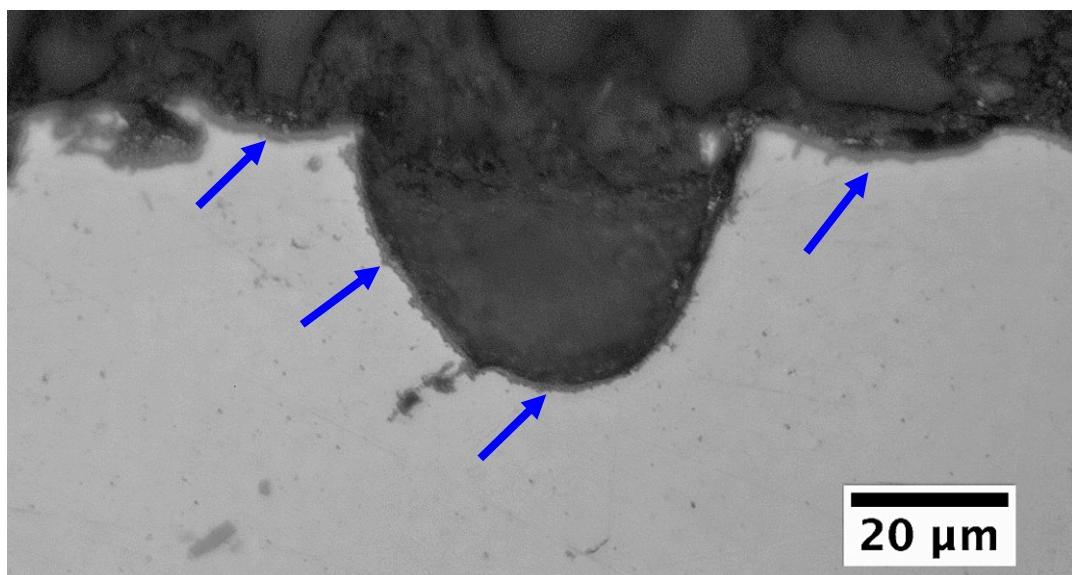


Figure 26. Micrograph of a rescue hoist arm in cross-section showing the presence of an anodised layer on the surface of the component and within the etch pits, as indicated with blue arrows.

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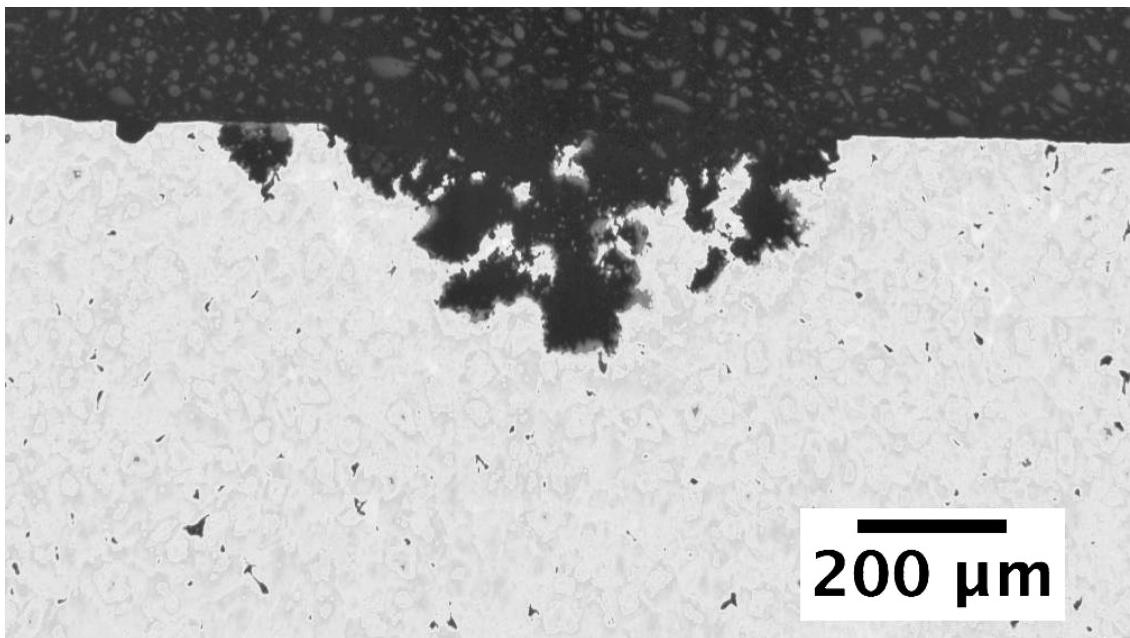


Figure 27. Micrograph of a rescue hoist arm in cross-section showing the corrosion pits had a branched and irregular structure.

The two rescue hoist arms were from the same manufacturing batch and both had fine etch pits present over their entire surfaces. These etch pits were found to be both anodised and painted, indicating that they formed prior to anodising. The existence of etch pits over all surfaces suggested that they formed when the parts were immersed in a bath during the pre-anodising process.

Corrosion pits were also present on both rescue hoist arms. The large size and localised nature of the corrosion pits suggested that they formed due to exposure to a surface contaminant. As the locations of the corrosion pits were consistent between the two rescue hoist arms and limited to the exterior surface of the body, it is likely that contamination occurred during a process which all parts were subjected to during manufacture or storage, for example parts handled with contaminated gloves or equipment, or stored on contaminated racks.

The corrosion pits formed some time after anodising. The surface etch pits may have caused discontinuities in the anodised surface layer, making the alloy susceptible to localised corrosion. It is also possible that the rescue hoist arms were stored for some time following anodising and prior to painting, during which time the corrosion pits began to form due to surface contamination. Following painting, the corrosion pits continued to grow undetected beneath the paint layer.

Due to the presence of significant surface etch pits and localised corrosion pits, the rescue hoist arms were considered no longer fit for purpose. The presence of the etch pits and, in particular, the larger corrosion pits introduced unquantifiable stress concentrations that could initiate cracks during subsequent in-service loading, both cyclic and sustained. As such, all rescue hoist arms from the same manufacturing batch were rejected.

4. Summary

Anodised aluminium alloy components are used extensively throughout the ADF aircraft fleet and in most cases the anodising process will have been performed correctly and significant etch pitting will not be present. Anodising remains an effective corrosion protection method for aluminium components, however it needs to be recognised, particularly by OEMs, that process control is crucial so that the benefits of anodising are not lost due to the formation of etch pits. This is especially so given that anodising is a batch treatment and therefore problems with a single batch can extend to numerous parts. This could potentially lead to a shortage of spares should an entire batch need to be rejected, or more importantly, could result in an entire batch of components developing cracking while in service. Fatigue cracking is by far the most common cause of failure of aircraft components, so the introduction of crack initiators at manufacture will only add to the problem.

In the examples provided in this report, the etch pits that formed during the anodising process also contributed to the growth of corrosion pits. The presence of large corrosion pits diminished the components' ability to perform as required. Of concern is that etch and corrosion pits can be present on a new component, but remain hidden by the paint scheme.

Awareness of the problems that can be associated with anodising, and effective reporting when defective components are found may assist in minimising the impact of anodising pitting defects on the ADF fleet.

5. Acknowledgements

The author would like to acknowledge the valuable contribution from Mr Jaime Calero for conducting the investigation into the main landing gear retractor actuator. The assistance of Mr Drew Donnelly with the investigation of the rescue hoist arm is also appreciated.

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